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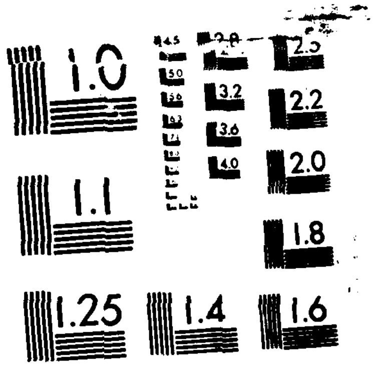

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NRL Memorandum Report 5766

Magnetic Reconnection in Laser-Plasma Interactions in a Background Magnetic Field

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Geophysical and Plasma Dynamics Branch
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May 9, 1986

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For laser irradiances I in the ablative regime ($I \leqslant 10^{14}$ Wcm^{-2}), focussed on a small solid target it is shown that magnetic field-reversed configurations, defined by the laser-produced self-generated magnetic field and an externally applied magnetic field perpendicular to the laser axis, are possible near the laser-target interaction region. Approximate conditions under which these field-reversed regions undergo driven reconnection are investigated. Magnetic reconnection of the background magnetic field with the laser-induced spontaneous magnetic field can lead to distortion and dissipation of the background magnetic field near the laser-target interaction region.

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CONTENTS

MAGNETIC RECONNECTION IN LASER-PLASMA INTERACTIONS IN A BACKGROUND MAGNETIC FIELD

I. INTRODUCTION

By generating large-scale (tens to hundreds of kilometers), long-lived (several hours) ionization structures and irregularities, the natural ionosphere and magnetosphere can be significantly disturbed by a high altitude nuclear explosion (HANE). Since these structures and irregularities can degrade communication systems operating in or through the near earth space plasma, it is of utmost importance to possess a detailed knowledge of a HANE evolution. Recently, laboratory simulations of a HANE have been started[1] at the Naval Research Laboratory using laser irradiation of small solid targets.

The manner by which exploding debris plasma couples into the background air is an important feature of the early time (first few seconds) evolution of a HANE. The spatial and temporal nature of the early time coupling could seed the evolution and structure of later time ionization irregularities and striations. This coupling can either by collisional (particle-particle), Larmor (magnetic), or collisionless[2] (wave-particle) depending on the densities and temperatures of the background plasma. Collisionless coupling proceeds via plasma microturbulence which in turn results from various plasma instabilities driven by the relative streaming between debris and air plasma. Turn-on conditions[3,4] for collisionless coupling, in the context of the current NRL laser experiment, have been derived. An important parameter in the

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excitation of the aforementioned plasma microinstabilities is the local magnetic field in the debris-air coupling region. If the magnetic field is small, several of the debris-air coupling instabilities will not be excited. As a result, in the context of laser-target interactions and associated plasma debris characteristics, a detailed description of the early time magnetic field evolution and morphology is important. Ref. 5 has summarized and discussed analytical models of magnetic field evolution and structure in laser-plasma interactions both with and without an externally applied magnetic field. In Ref. 6 it was shown that electron thermal conduction near the target can be modified due to the self-generated magnetic fields leading to preferential debris back-jetting along the laser axis. However, since the self-generated magnetic fields are known to be azimuthal[7] about the laser axis, it is possible that field-reversed magnetic field regions near the target could be generated in the presence of the externally applied magnetic field perpendicular to the laser beam axis as schematically shown in Fig. 1. Such magnetic field-reversed configurations could then undergo reconnection and lead to a distortion and dissipation of the local background magnetic field near the laser-target interaction region.

In this report we investigate the conditions under which such magnetic field-reversed configurations could undergo reconnection. In Section II, we discuss the source of the self-generated magnetic fields and subsequent generation of a field-reversed configuration. In Section III, the possibility, on hydrodynamic time scales, of driven or forced reconnection, between radially convected self-generated magnetic fields and externally applied magnetic fields is discussed. Such reconnection has the effect of locally distorting and dissipating the background magnetic field topology near the field-reversed region. Finally, in Section IV the results of this study are summarized and discussed. The implications of reconnecting

field-reversed regions on plasma jetting and debris coupling are also presented.

II. SELF-GENERATED MAGNETIC FIELDS AND FIELD-REVERSED CONFIGURATIONS

The evolution of the magnetic field in laser-plasma interactions is determined from Faraday's law and the generalized Ohm's law[8]:

$$\frac{e^2}{m_e}\left[\underline{E} + \underline{V} \times \underline{B} - \frac{1}{n_e e}\underline{J} \times \underline{B} + \frac{1}{n_e e}\nabla p_e - \frac{1}{n_e}\underline{R}\right] - \frac{d}{dt}\left(\underline{j}/n_e\right) = 0 \qquad (1)$$

where $\underline{V}$ is the hydrodynamic velocity, $\underline{j}$ is the current, $\underline{E}$ the electric field, $\underline{B}$ the magnetic field, e the charge, n_e the electron density, m_e the electron mass, p_e the pressure, and $\underline{R}$ represent momentum sources through collisions (thermoelectric, resistive, and cross-field). The terms in brackets in eq. (1) are the various current generating sources: the $\underline{V} \times \underline{B}$ is the usual electro-motive induction force, the $\underline{J} \times \underline{B}$ term is the Hall effect and the ∇p_e is due to electron pressure. Assuming $\underline{R} = n_e \eta \underline{J}$, where η is the resistivity, and inserting Eq. (1) into Faraday's law we find that the evolution of the magnetic field $\underline{B}$ can be written, to lowest order,

$$\frac{\partial \underline{B}}{\partial t} = \nabla \times \underline{V} \times \underline{B} + \frac{c^2 \eta}{4\pi}\nabla^2 \underline{B} - \frac{c}{eN_e}\nabla N_e \times \nabla T_e \qquad (2)$$

Higher order magnetic field source terms, i.e., terms like $\nabla N_e \times \nabla T_e$ in eq. (2), have also been studied.[9] Radiation pressure effects have been neglected in Eq. (2) since they can be shown to be small for laser power densities I in the ablative regime $\left(I \lesssim 10^{14}\ \mathrm{W/cm^2}\right)$. The source[7] of the magnetic field (last term in Eq. (2)) is nonzero if ∇N and ∇T are nonparallel and will be determined by the geometrical configuration of the laser-plasma interaction. A cylindrically symmetric laser beam will produce a plasma which expands in the direction normal to the target plane

and is symmetric about its expansion direction. From symmetry considerations there can be no azimuthal density or temperature gradients. During the laser heating of the target, it is reasonable to assume that the dominant contribution to the source term in Eq. (1) is derived from a temperature gradient in the radial direction and a density gradient in the direction of the target normal. Due to the finite radial extent of the laser beam a radial temperature gradient will exist near the edge of the focal spot. This combination of ∇T and ∇N will generate a magnetic field in the azimuthal direction in the form of a torus. The self-generated magnetic field is convected radially by the hot expanding laser plasma as shown experimentally in Ref. 7.

For very short times after the laser pulse has been terminated, i.e., for time scales where the hydrodynamics is not important, e.g., for $t \lesssim t_H \sim a/C_s \sim$ several nanoseconds for $a \approx 1$ mm, $C_s \approx 10^7$ cm/sec where a is a typical target size and C_s a typical sound speed (for aluminum at $t \sim 100$ ev), the hydrodynamic response of the plasma (second term, in Eq. (2)) can be neglected. Since the diffusive term in Eq. (2) can also be neglected on these fast time scales one can solve Eq. (2) finding

$$B_\theta(t) \approx \int dt \, \frac{c}{eN_e} \frac{\partial N_e}{\partial z} \frac{\partial T_e}{\partial r} \qquad (3)$$

where we have taken the density gradient to be purely axial and the temperature gradient to be radial. For $\Delta t \approx 4 \times 10^{-9}$ sec, $T_e \approx 0.5$ kev, $L_N \approx L_T \approx 10^{-4} - 10^{-3}$ cm $\left(L_N^{-1} = N_e^{-1}\ \partial N_e/\partial z,\ L_T^{-1} = T_e^{-1}\ \partial T_e/\partial r\right)$ we find $B_\theta \approx 10^3 - 10^4$ G. The magnitudes of the self-generated magnetic fields as given by Eq. (3) are in agreement with those obtained using exact solutions[10] of Eq. (2). For a constant external magnetic field on the order of 10^3 G, approximate magnetic field-reversed configurations can be achieved as depicted in Fig. 1.

III. DRIVEN MAGNETIC RECONNECTION

On hydrodynamic time scales the outward radial flow of coronal plasma near the laser-target interaction region can convect the self-generated magnetic field into the background magnetic field[11,7]. The possibility of driven reconnection between these two magnetic fields must be considered. This model is illustrated in Figure 2. Similar scenarios dealing with the interaction between streaming high β plasma and stationary low β plasma in magnetic-field reversed configuration have also been discussed[12,13] with regard to both space and laboratory plasmas.

With reference to Fig. 2, an expanded version of the magnetic field-reversal region in Fig. 1, the magnetic fields defined by the self-generated and external fields approach each other with velocity V in the x-direction. In the vicinity of the neutral regions where $B \simeq 0$ (shown in Fig. 2 with approximate planar dimensions $\Delta x \Delta y$) the magnetic fields will diffuse and reconnect (using Eq. (2)) on a time scale $t_R = 4\pi L_x^2/\eta c^2$ where L_x is the scale length of the magnetic field gradient in the neutral region. Since $\nabla \times \underset{\sim}{B} = \nabla B_y/\Delta x$ can be large in the neutral region, large currents $\underset{\sim}{J} = (c/4\pi)\nabla \times \underset{\sim}{B}$ in the z-direction can also be generated. Figure 3 gives approximate reconnection times as a function of L_x for several electron temperatures T_e using classical Spitzer resistivity $\eta = 1.15\times10^{-14}$ $Z \ln \Lambda\ T_e^{-3/2}(\mathrm{ev})$ sec with $\ln \Lambda = 24 - \ln [n_e^{1/2}(\mathrm{cm}^{-3})/T_e(\mathrm{eV})]$ and Z the charge state. For example, for $T_e = 100$ eV and $L_x = 10^{-2}$ cm, $t_R = 10^{-9}$ sec.

It is well known that the $\nabla \times \underset{\sim}{B}$ driven currents, if of sufficient magnitude, can excite plasma microinstabilities which can increase the classical resistivities to such an extent that the time scale for reconnection is considerably reduced. Several candidate plasma microinstabilities are (14 the (1) Buneman instability, (2) ion acoustic, (3) beam-cyclotron, (4) lower hybrid drift instability, (5) modified two

stream, and (6) ion cyclotron drift. Of these, the ion acoustic instability and lower hybrid drift instability have received the most attention. For the ion acoustic instability, one requires[14] a relative electron-ion drift v_d

$$v_d > v_c = (2k_B T_i/m_e)^{1/2} \tag{4}$$

for $0.2 < T_e/T_i < 5$ where

$$V_d = \frac{c}{4\pi n_e e} |\nabla \times B| = \frac{c\Delta B_y}{4\pi n_e e \Delta x} \tag{5}$$

Inserting this expression for v_d into Eq. (4) we find

$$\Delta x \leq \Delta x_c = \frac{Bc}{4\pi n_e e} \left(\frac{m_e}{2k_B T_i}\right)^{1/2} \tag{6}$$

for excitation of the ion acoustic instability where $B = B_y$. Figure 4 displays Δx_c for fixed B and T_i as a function of the electron density n_e. For example, for $n_e = 10^{17}$ cm^{-3}, $B = 10^3$ G, and $T_i = 10$ eV ion acoustic instability will be excited for neutral sheet widths $\Delta x \lesssim 10^{-3}$ cm. Figure 5 shows ΔX_c for higher fixed magnetic fields $B = 10$ kG and $T_i = 10{,}100$ eV. For these stronger fields broader current sheets will lead to excitation of the ion acoustic instability.

Several nonlinear theories of the ion acoustic instability have been proposed. Sagdeev[15] has reported an anomalous collision frequency associated with the ion acoustic instability of magnitude

$$\nu^* = 10^{-2}(T_e/T_i)(v_d/v_e)\omega_{pe} \tag{7}$$

with v_e the electron thermal velocity and ω_{pe} the electron plasma frequency. Defining an anomalous resistivity by $\eta^* = (4\pi/\omega_{pe}^2)\nu$ where ν is the effective collision frequency one finds for the ion-acoustic instability

$$\eta^* = 4\pi \times 10^{-2}(T_e/T_i)(v_d/v_e)\omega_{pe}^{-1} \tag{8}$$

Figure 6 gives the reconnection time scales assuming $\eta = \eta^*$ as given by Eq. (8) as a function of L_x the magnetic field gradient scale length for several electron densities and taking $T_e/T_i = 5$ and $v_d/v_e = 0.3$. For $n_e = 10^{17}$ cm^{-3} and $L_x = 10^{-2}$ cm, $t_R^* = 10^{-11}$ sec. This leads to an approximate two orders of magnitude reduction in the reconnection time compared with classical resistivity $t_R = 10^{-9}$ sec for similar scale lengths (see Fig. 3).

In terms of the merging rate $M = V_{in}/V_A$ where V_{in} is the velocity of field line transport in the diffusion or neutral region and V_A is the Alfvén velocity using $B_y(\infty)$ one finds $M^*/M = t_R/t_R^* \gg 1$.

The lower hybrid drift (LHD) instability has also been invoked to produce anomalous resistivity triggering rapid reconnection in the earth's magnetotail[16] and theta pinch implosions[17] in laboratory plasmas. The LHD instability can be excited with broader neutral sheet widths or smaller $\nabla \times B$-driven current densities. However, it has been shown[18] that the LHD instability is localized away from the neutral line and is stabilized in the high β region near the neutral line. From this it is inferred that LHD driven anomalous resistivity cannot penetrate to the neutral line and, thus, not be effective in enhancing rates of reconnection.

IV. SUMMARY AND DISCUSSION

In this report we have shown that, for laser irradiances I in the ablative regime ($I \leq 10^{14}$ Wcm^{-2}) focussed on small solid targets magnetic field-reversed configurations, defined by the laser-induced self-generated magnetic field and an externally applied magnetic field perpendicular to the laser axis, are possible near the laser-target interaction region. Approximate conditions under which these field-reversed regions may undergo driven reconnection are investigated using parameters typical of the NRL laser/HANE experiment. In this report we have only discussed onset criteria for fast driven reconnection. Nonlinear simulations[19,20] of driven reconnection have shown that (1) magnetic field energy near the field-reversal region is converted to particle kinetic energy, (2) electrons and ions are preferentially heated parallel to the magnetic field (y-direction in Fig. 2) although some heating also occurs perpendicular to the initial magnetic field (x-direction in Fig. 2), and (3) electrons and ions are accelerated perpendicular to the magnetic field (z-direction in Fig. 2) due to inductive electric fields E_z associated with reconnection. These three nonlinear effects can affect the evolution of the debris plasma at early times near the target. In particular, if the background magnetic field is annihilated in certain regions near the target due to reconnection with laser self-generated magnetic fields, then the electromagnetic stabilization criterion (which relies on large Alfvén velocities) may be more restrictive in these regions for the turn-on of various streaming instabilities, e.g., the magnetized ion-ion instability. Since these effects will only occur in field-reversed regions near the target (see Fig. 1) debris coupling could be asymmetric in the plane perpendicular to the laser axis and close to the target. In addition, if electrons and ions are heated preferentially in certain regions near the target, electron

shielding effects (which rely on large ion sound speeds) may not be as important, e.g., the unmagnetized ion-ion instability. Finally, preferential ion and electron accelerations, due to reconnection driven inductive electric fields, could lead to off-axis jetting back toward the laser (out-of-page in field-reversal region in Fig. 1).

Future studies of possible magnetic reconnection in the NRL laser/HANE experiments will include (1) numerical MHD simulations (2) studies of inhomogeneities along the magnetic field direction (y-direction in Fig. 2), and (3) quantitative effects on debris-air coupling.

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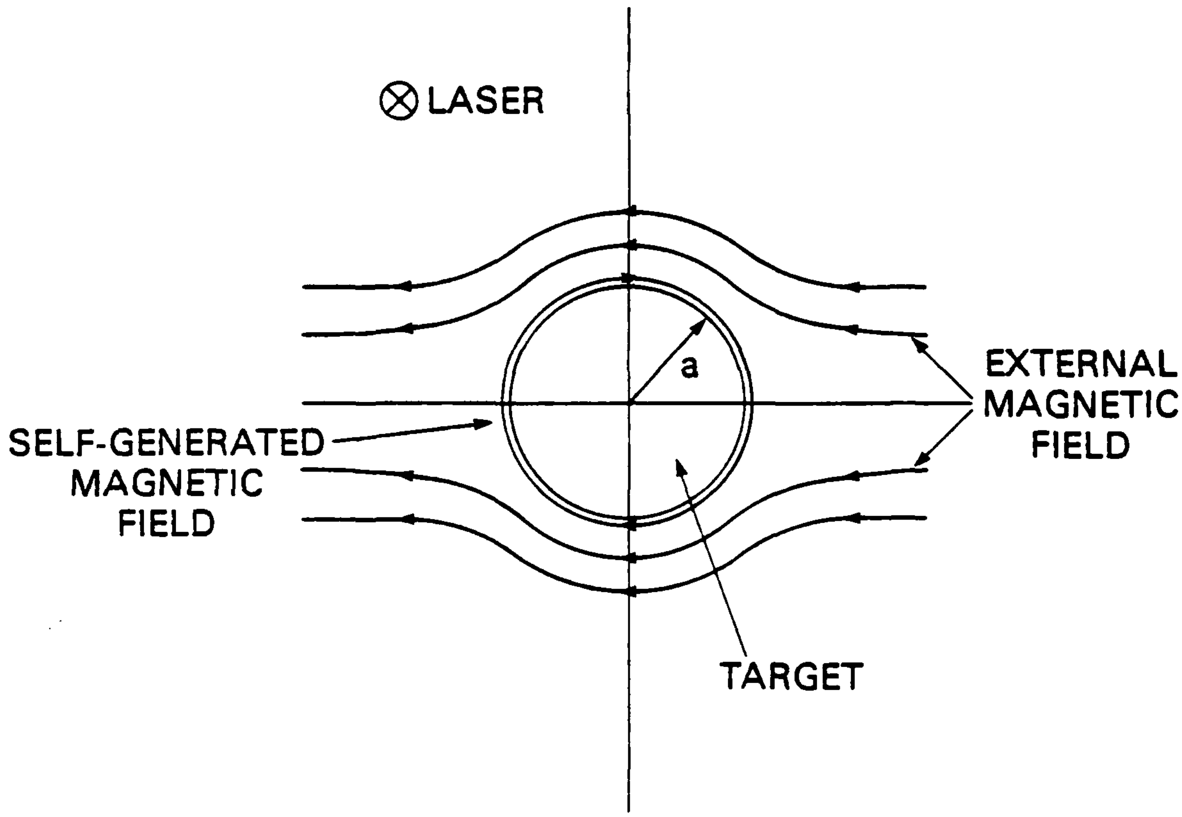

Fig. 1 Schematic representation of region near target showing self-generated magnetic field, external magnetic field, and field-reversed region. The target is in plane of paper with laser directed into plane of paper. The dimension a is approximately 10^{-1} cm.

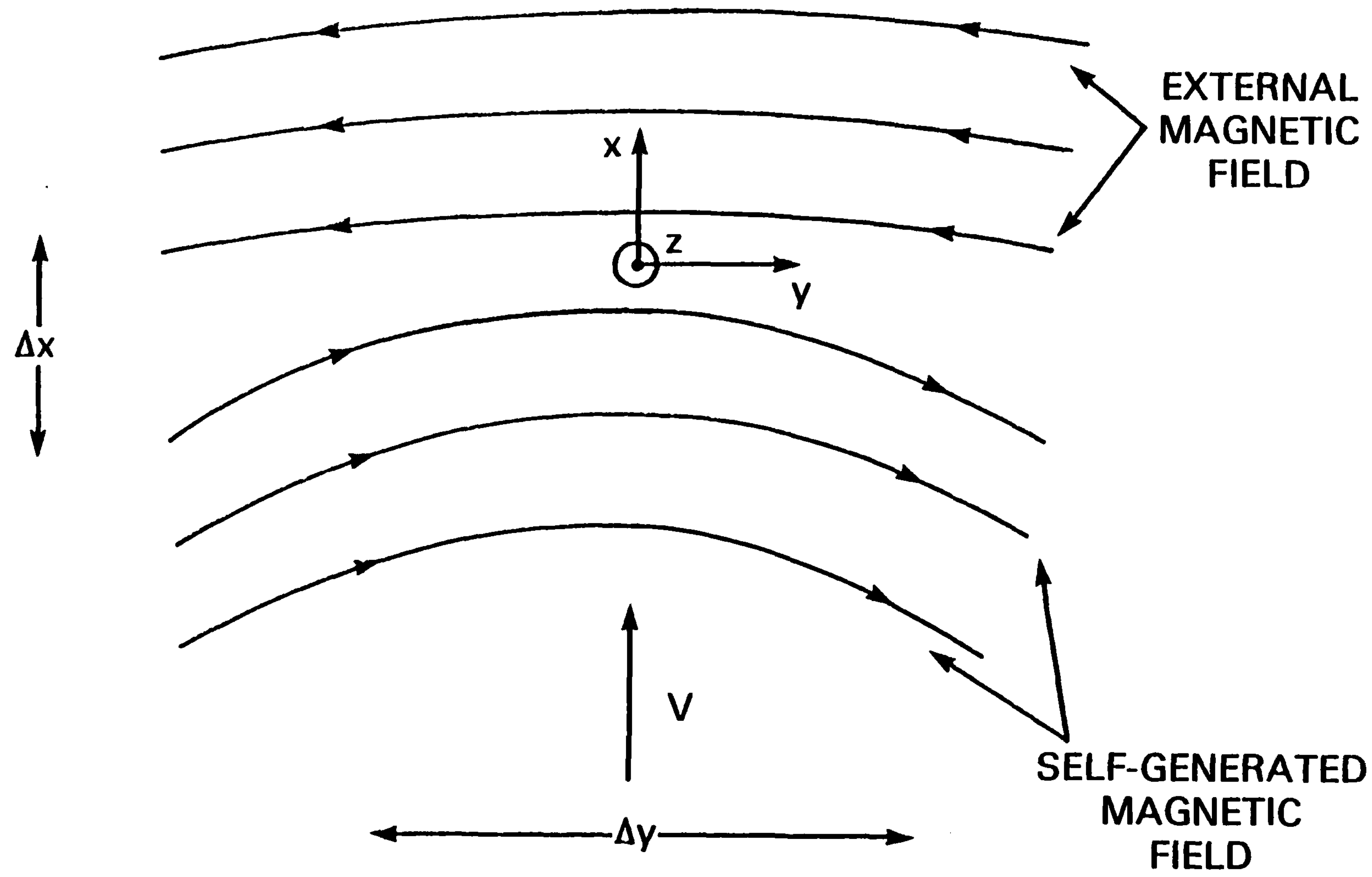

Fig. 2 Schematic model of driven reconnection. Diffusion region has approximate dimensions $\Delta \times \Delta y$ and is centered near $x=y=z = 0$ using the coordinate system shown.

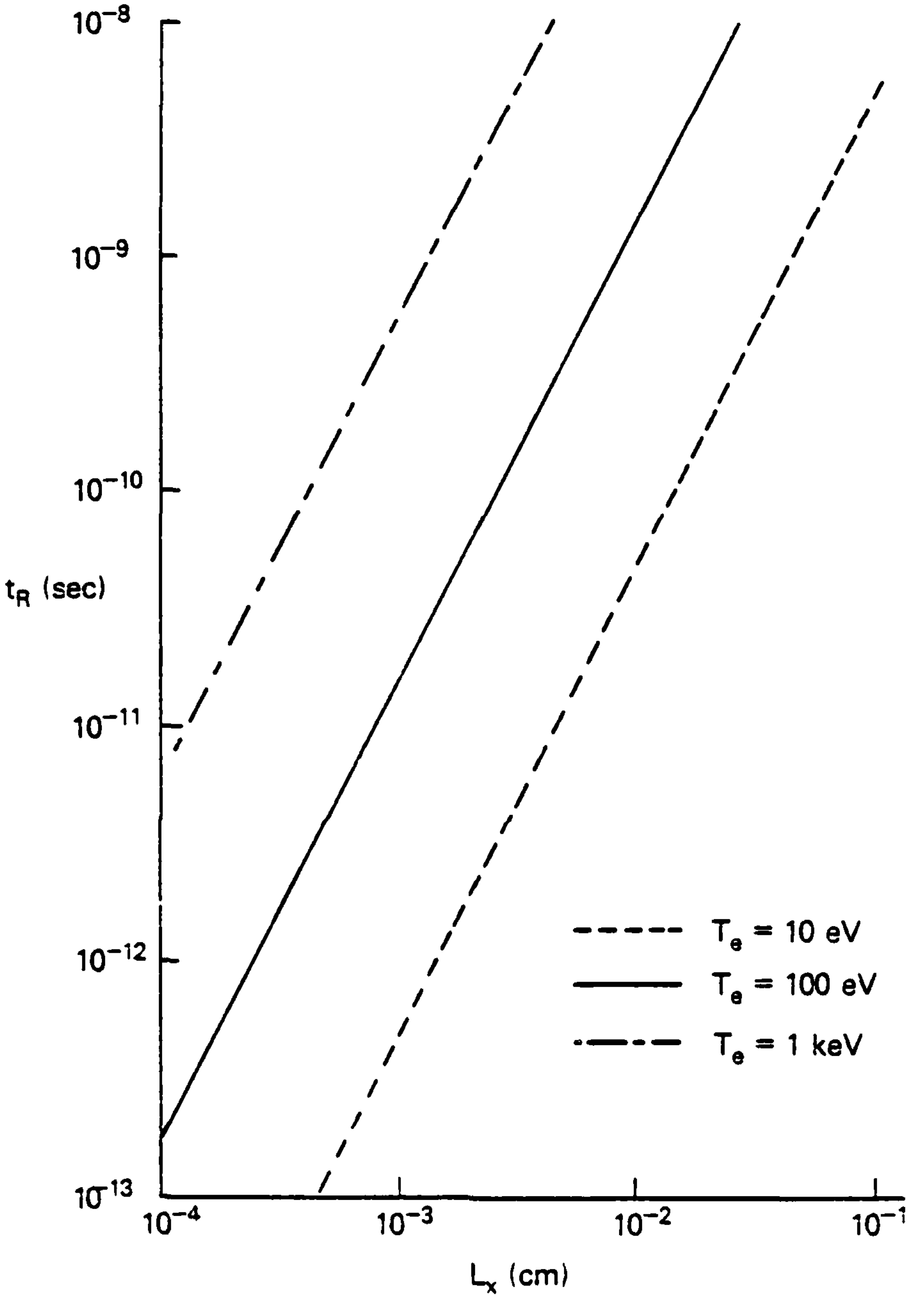

Fig. 3 Plot of reconnection time t_R (sec) using classical resistivity vs. L_x (cm), the magnetic field gradient scale length, for T_e = 10, 100, 10^3 eV.

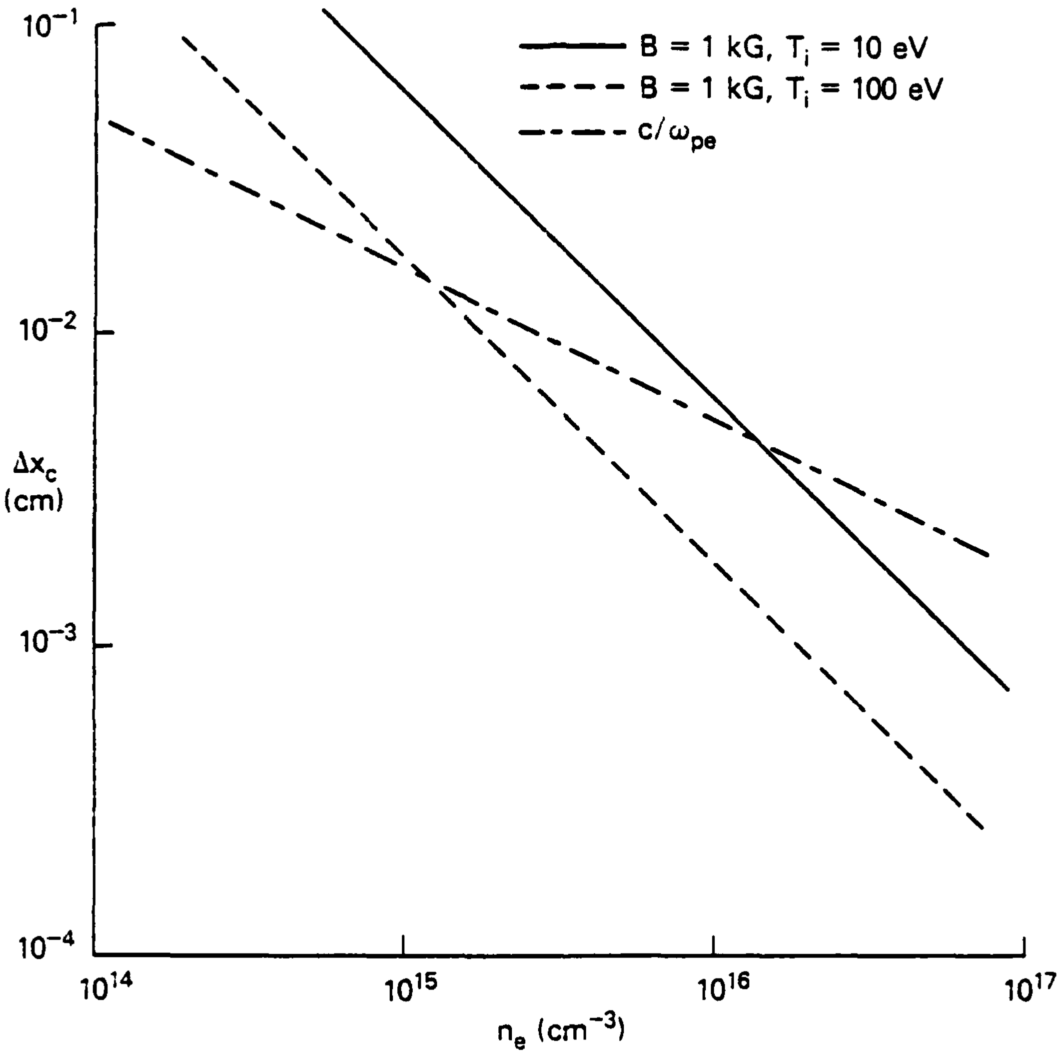

Fig. 4 Plot of neutral sheet width Δx_c (cm) for excitation of ion acoustic instability vs. electron density n_e (cm^{-3}) for B = 10^3 G, T_i = 10, 100 eV.

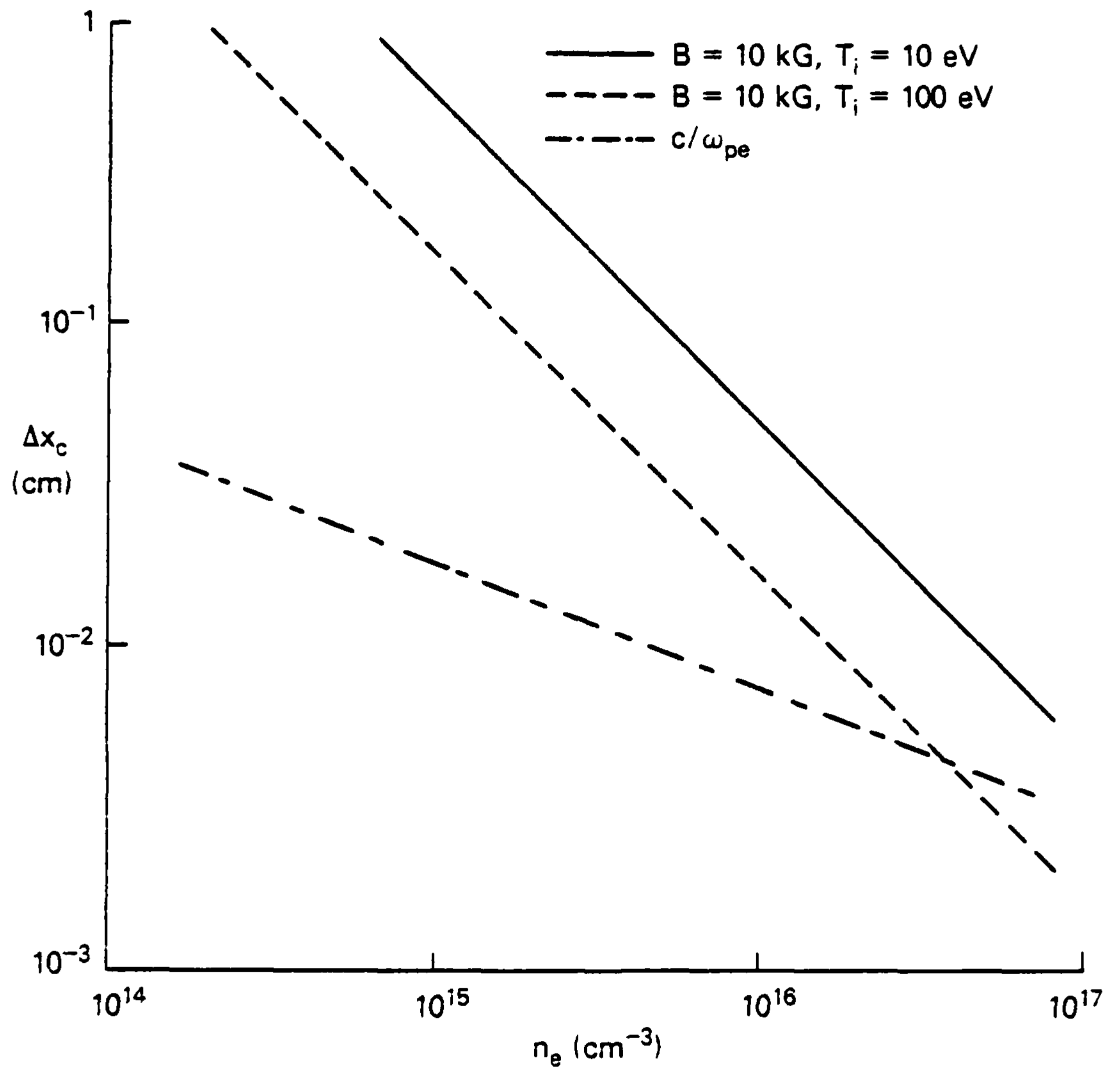

Fig. 5 Plot of neutral sheet width Δx_c (cm) for excitation of ion acoustic instability vs. electron density n_e (cm^{-3}) for $B = 10^4$ G, $T_i = 10$, 100 eV.

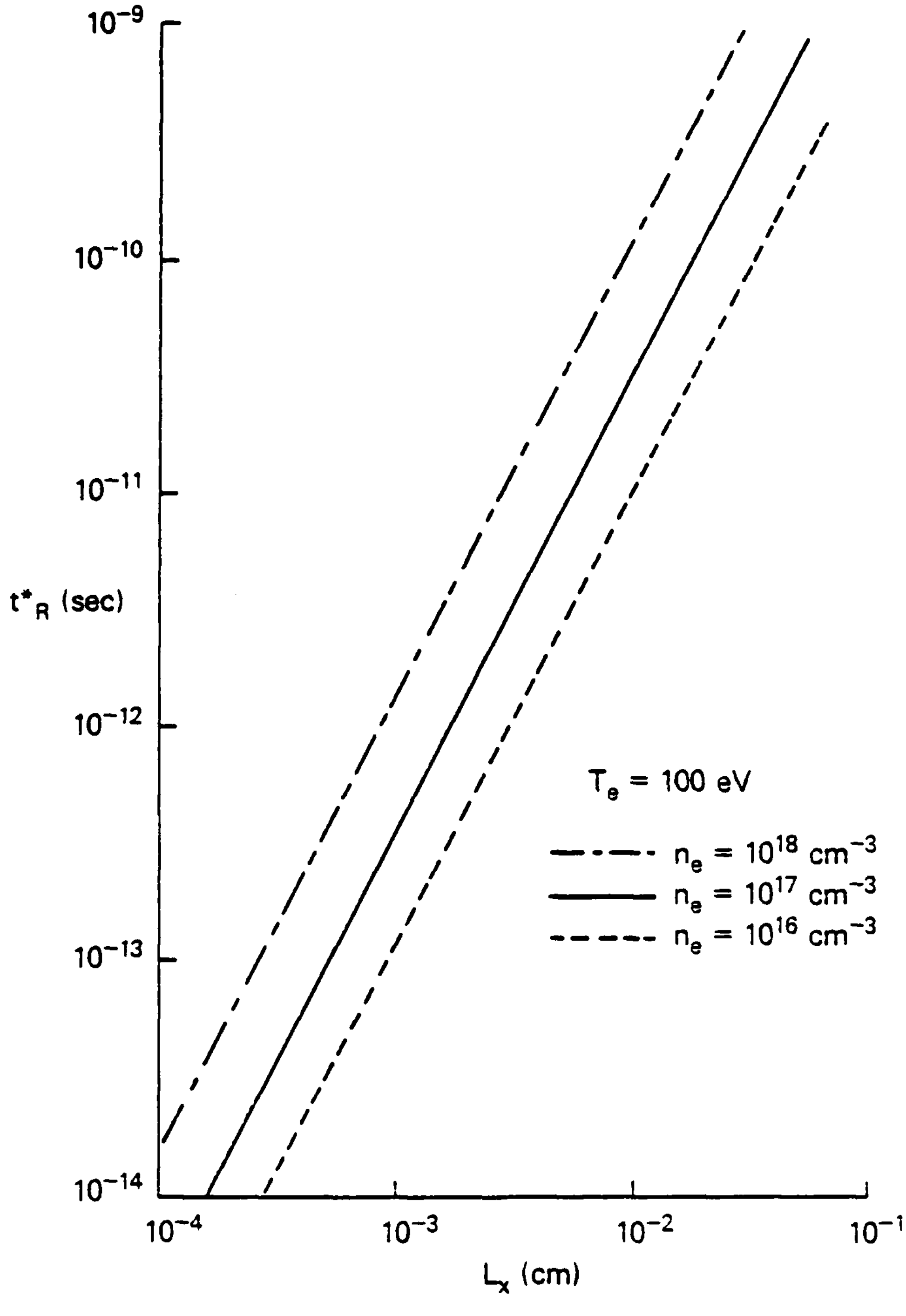

Fig. 6 Plot of reconnection time t_R* (sec) using ion acoustic anomalous resistivity vs. L_x for several electron densities $n_e = 10^{16}$, 10^{17}, 10^{18} cm^{-3}.

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